Earth-Science Reviews 177 (2018) 238–247

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Evaluating the relationship between climate change and volcanism

Claire L. Cooper[a,b,*], Graeme T. Swindles[a], Ivan P. Savov[b], Anja Schmidt[c,d], Karen L. Bacon[a]

[a] School of Geography, University of Leeds, Leeds LS2 9JT, UK
[b] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[c] Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW, UK
[d] Department of Geography, University of Cambridge, Downing Place, Cambridge, CB2 3EN, UK

ARTICLE INFO

Keywords:
Volcanism
Climate
Deglaciation
Unloading effect
Tephra

ABSTRACT

Developing a comprehensive understanding of the interactions between the atmosphere and the geosphere is an ever-more pertinent issue as global average temperatures continue to rise. The possibility of more frequent volcanic eruptions and more therefore more frequent volcanic ash clouds raises potential concerns for the general public and the aviation industry. This review describes the major processes involved in short- and long-term volcano–climate interactions with a focus on Iceland and northern Europe, illustrating a complex interconnected system, wherein volcanoes directly affect the climate and climate change may indirectly affect volcanic systems. In this paper we examine both the effect of volcanic inputs into the atmosphere on climate conditions, in addition to the reverse relationship – that is, how global temperature fluctuations may influence the occurrence of volcanic eruptions. Explosive volcanic eruptions can cause surface cooling on regional and global scales through stratospheric injection of aerosols and fine ash particles, as documented in many historic eruptions, such as the Pinatubo eruption in 1991. The atmospheric effects of large-magnitude explosive eruptions are more pronounced when the eruptions occur in the tropics due to increased aerosol dispersal and effects on the meridional temperature gradient. Additionally, on a multi-centennial scale, global temperature increase may affect the frequency of large-magnitude eruptions through deglaciation. Many conceptional models use the example of Iceland to suggest that post-glacial isostatic rebound will significantly increase decompression melting, and may already be increasing the amount of melt stored beneath Vatnajökull and several smaller Icelandic glaciers. Evidence for such a relationship existing in the past may be found in cryptotephra records from peat and lake sediments across northern Europe. At present, such records are incomplete, containing spatial gaps. As a significant increase in volcanic activity in Iceland would result in more frequent ash clouds over Europe, disrupting aviation and transport, developing an understanding of the relationship between the global climate and volcanism will greatly improve our ability to forecast and prepare for future events.

1. Introduction

It is already well established that various aspects of the Earth system, such as the atmosphere, geosphere and cryosphere, regularly interact through the exchange of materials and energy (Webster, 1994; Pielke et al., 1998). The global impact of large explosive and effusive eruptions, such as the 1991 eruption of Mount Pinatubo (Philippines, VEI (Volcanic Explosivity Index) 6) (McCormick et al., 1995), the 1815 eruption of Tambora (Indonesia, VEI 7) (Stothers, 1984), or the 1783–1784 eruption of Laki (Iceland, VEI 6) (Thordarson and Self, 2003), can be clearly seen in historical and environmental records (Robock, 2000). Injection of large quantities of volcanogenic material, such as fine tephra or volcanic gases (e.g. sulphur dioxide, carbon dioxide, hydrogen sulphide), into the stratosphere or troposphere can cause so-called `dust veil' events (Lamb, 1970) with the potential to dramatically alter the Earth's climate on a regional or global scale for short periods of time (typically on the scale of several years to decades). The year following the 1815 eruption of Mt. Tambora, for example, is often referred to as the 'Year Without a Summer' – global temperatures are estimated to have dropped by 0.4–0.7 °C (Stothers, 1984), causing several weather anomalies, particularly across the northern hemisphere, and placing considerable strain on agriculture worldwide (Stothers, 1999).

The relationship between a changing global climate (specifically, one experiencing a warming period) and a potential change in the patterns of volcanic eruption frequency or intensity is relatively unexplored. McGuire (2010) suggests that periods of `exceptional climate change' may be associated with increased levels of hazardous

* Corresponding author at: Office 10.11, School of Geography, University of Leeds, LS2 9JT, UK.
E-mail address: gyclc@leeds.ac.uk (C.L. Cooper).

https://doi.org/10.1016/j.earscirev.2017.11.009
Received 23 March 2017; Received in revised form 25 September 2017; Accepted 10 November 2017
Available online 20 November 2017
0012-8252/ © 2017 Elsevier B.V. All rights reserved.

geological and geomorphological activity, based on early Holocene records and contemporary observations of glacier retreat, measurements of ground instability, and estimations of melt production beneath Iceland (Oerlemans et al., 1998; Óladóttir et al., 2011; Magnusdottir et al., 2013). An increase in volcanic activity as a response to climate change has previously been suggested by multiple studies (Jull and McKenzie, 1996; Pagli and Sigmundsson, 2008; Watson et al., 2016a, 2016b). Such an escalation would have significant consequences, not only for populations in the immediate vicinity of volcanically active regions, but also for the global community as a whole. As of 2014, approximately 100,000 commercial flights occur per day worldwide (ATAG, 2016). Jet aircraft are extremely vulnerable to damage caused by interactions with even low concentrations of airborne ash particles, which may cause electronic failures, or severe abrasion on the turbine fans (Grindle and Burcham, 2003). Since 1976, approximately two severely damaging encounters between aircraft and volcanic ash clouds have occurred per year (Guffanti et al., 2010). Between 1944 and 2006, volcanic activity necessitated the closure of > 100 airports in 28 countries on 171 separate occasions (Guffanti et al., 2009). The economic and social disruption caused by such events may be most clearly illustrated by reference to the relatively minor (VEI 3) eruption of Eyjafjallajökull in 2010, which resulted in the closure of a large region of airspace across Europe, causing the loss of approximately US $1.7 billion in revenue to various airlines in the space of a week (Mazzocchi et al., 2010). The presence of volcanic ash also presents a hazard to human health and the health of livestock, particularly with regards to respiratory systems (Horwell and Baxter, 2006), even at relatively small concentrations (Horwell, 2007).

The 2010 eruption of Eyjafjallajökull also precipitated a sudden focus in scientific research into the understanding and mitigation of volcanic ash hazards, particularly with regards to northern Europe and volcanism in Iceland. The unusual geochemical profile of Iceland (a result of its unique geological location above the confluence of a mid-oceanic spreading ridge and a deep-seated mantle plume; Oskarsson et al., 1985) and the relative wealth of data concerning eruptions at the Icelandic sites, in addition to the wide range of locations affected by Icelandic eruptions, make the region ideal for the study of past volcanic activity. Icelandic tephras have been identified in Scotland, England, Ireland, Germany, Sweden, Arctic Norway, Poland, Estonia and the Faroe Islands (Pilcher et al., 2005; Swindles et al., 2011; Watson et al., 2017), forming a comprehensive record of Icelandic ash deposition across Europe. If the proposed relationship between periods of global warming and `flare-ups' in volcanic activity can be shown to exist, the ramifications to modern society, particularly with regards to aviation and the agricultural industry, may be significant.

This review examines the established links between volcanism and subsequent surface cooling, and assesses the potential for correlation between periods of atmospheric warming and an increase in the frequency of volcanic eruptions, with a focus on Iceland and tephra fallout across northern mainland Europe and the United Kingdom. Iceland is frequently referred to as a case study, as much of the existing work pertinent to this review was conducted with a European focus. A wide selection of the existing evidence are considered; however, many of the techniques and hypotheses suggested below are still speculative, and projections of future climate change remain highly contentious at the time of writing (March 2017).

2. Volcano-climate forcing

2.1. Short-term events

A link between large volcanic eruptions and variations in regional and global climate variability has been surmised to exist for at least several centuries. The earliest example of serious scientific thought on the matter was published by Benjamin Franklin in 1784, following the catastrophic fissure eruption of Laki (also called Lakagigar) in Iceland in 1783 (Franklin, 1784). Franklin linked the observations of a `haze' or `mist' across much of Europe in the following months to the significant negative temperature anomalies which characterised that summer and the following winter. It is now known that the so-called mist was caused by the release of approximately 122 megatons of sulphur dioxide (SO_2) from the Laki fissure, 95 Mt. of which were injected into the lower stratosphere, ensuring widespread atmospheric dispersal (Thordarson and Self, 2003). Once injected into the atmosphere, SO_2 reacts with ambient water vapour to form aerosol mixtures of sulphuric acid (H_2SO_4) and water. This blanketing of the upper atmosphere is believed to have caused significant solar dimming for a period of several months as a result of aerosol particles leading to enhanced scattering of incoming solar radiation (Schmidt, 2013). In the lower atmosphere, sulphur aerosols may also act as cloud condensation nuclei (Jacoby et al., 1999), furthering the surface cooling effect. There is evidence to suggest that this alteration to surface temperatures may have caused a weakening of the monsoon circulation in 1784 through a reduction of the summer temperature contrast between the mid-latitudes and the equator, resulting in abnormally low precipitation and drought in Africa and India (Oman et al., 2006).

Several other large eruptions have had notable effects on the global climate. The eruptions of Krakatoa (Indonesia, August 1883), Agung (Indonesia, February 1963) and El Chichón (Mexico, March 1982) each had a short-term (several months to years) impact on surface temperatures and other climate factors (Self et al., 1981; Robock, 2000). In each case, the eruptions in question were explosive in nature, with a volcanic explosivity index (VEI; a quantitative measurement of the volume of material ejected during an eruption; Newhall and Self, 1982) of 5 or greater; however, some explosive eruptions of a similar magnitude, such as the eruption of Mt. St Helens in 1980, have only negligible atmospheric effects (Robock and Mass, 1982). The determining factor in an eruption's climatic impact, therefore, is not the volume of material ejected from the vent, but whether a significant amount of that material achieves stratospheric injection (Robock, 2000). These occurrences are often referred to as volcanic aerosol clouds, or `dust veil' events, though in actuality solid particles such as dust and ash make up a relatively small percentage of the active components in volcanically-induced climate change (Lamb, 1970). Such fragments typically have a low residence time (generally on the order of a few months; Robock, 2000) in the atmosphere, and their effects disappear once the particles fall out and settle (Robock, 2000).

The contribution of volcanic gases to atmospheric forcing is much more significant than that of ash particles. The most abundant volcanic gases are those that are already at relatively high concentrations in our atmosphere (such as H_2O, N_2 and CO_2), and as such have only a minimal effect; however, other atmospheric contributors, such as sulphur compounds (e.g. SO_2, H_2S) have a much greater impact. These gases react with ambient OH and H_2O molecules to form aerosols such as H_2SO_4. If carried into the stratosphere by a volcanic column, these particles rapidly achieve global coverage, sometimes circulating the globe in as little as 3 weeks (Robock and Matson, 1983; Bluth et al., 1992). The dominant effect of such an aerosol cloud is to greatly (albeit briefly) increase the planetary albedo by backscattering incoming solar radiation, resulting in net cooling at the surface. On a similar timescale, the aerosol particles also act as a catalyst for ozone depletion reactions, which may result in anomalous regions of net surface warming, particularly in polar and mid-latitude regions (Solomon, 1999). This effect, in addition to aerosol heating by thermal infrared and near-infrared solar radiation, is dominant in the lower stratosphere (Oman et al., 2006). However, the overall net effect of such short-term aerosol releases is always one of mild cooling, typically to < 1 °C lower than ambient conditions (Rampino et al., 1988; Santer et al., 2016) (Fig. 1).

The geographic location of the initial eruption also plays a factor in determining an eruption's atmospheric impact (Robock, 2000). Dominant patterns of air circulation enable a more global dispersal of aerosols from tropical eruptions, whereas airborne material from high-

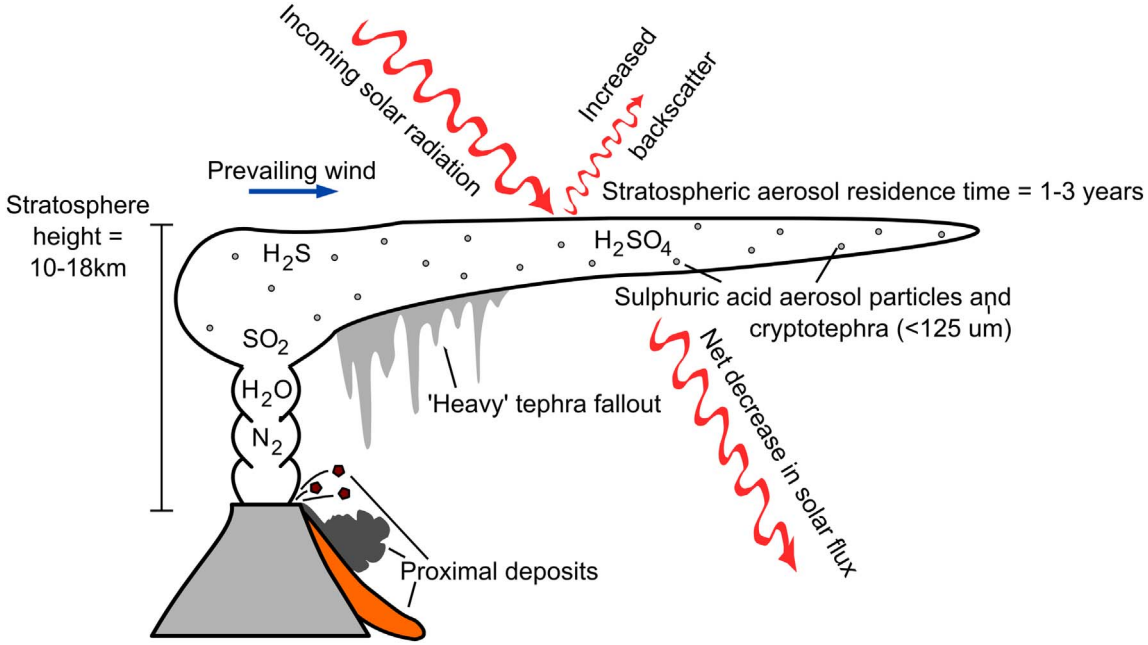

Fig. 1. Schematic of volcanic inputs to the atmosphere. Most tephra particles will fall out within a time period of days to weeks, while lighter emissions, such as gases and tephra particles < 125 μm in diameter may have a residence time of several months to years. Chemical species with a naturally high atmospheric abundance (such as CO_2, H_2O and N_2) will have a much lesser effect than less common species, such as SO_2. After Robock, 2000.

latitude eruptions is more likely to remain in the hemisphere into which it was injected (Oman et al., 2005). In addition, stratospheric warming centred close to the equator increases the meridional temperature gradient, strengthening the polar vortex and causing alterations in stratospheric circulation (Robock and Mao, 1992; Kirchner et al., 1999; Fischer et al., 2007). However, the complexities in the response of the atmosphere to the asymmetric cooling effects produced by even large volcanic events are as yet relatively poorly understood. The temperature anomalies which occur following volcanic aerosol injection are far from homogeneous (Haywood et al., 2013; Svensson et al., 2013; Ridley et al., 2015). Baldini et al. (2015) assert that higher latitude eruptions in either hemisphere may also have significant atmospheric effects by causing cooling in one hemisphere relative to the other, forcing migration of the Intertropical Convergence Zone (ITCZ). Current southward migration of the ITCZ in response to anthropogenic aerosol emissions is thought to be a major cause of frequent droughts experienced by the Sahel region of Africa (Hwang et al., 2013), and is a major control of air currents and associated precipitation in equatorial and low-latitude areas (Haug et al., 2001; Ridley et al., 2015).

2.2. Long-term events

In all observed incidences, volcanic aerosols are typically short-lived, with the result that their effects are generally only experienced on an interannual scale (Robock, 2000). However, there have previously been suggestions that explosive volcanic eruptions may also have longer-lasting `knock-on' effects. One such proposal is that large tropical eruptions may affect the magnitude of subsequent El Niño events, though the topic remains controversial (Self et al., 1997; Maher et al., 2015). Multiple attempts have been made to establish a causative link between eruption events and the onset of El Niño cycles through analysis of proxy data (Adams et al., 2003) or numerical modelling (Meehl and Washington, 1996; Boer et al., 2000); however, while the analyses do suggest the possibility of a connection between explosive volcanism and the El Niño/Southern Oscillation (ENSO) phenomenon, discrepancies in event timings and the influence of other factors on the likelihood of ENSO variations continue to cause uncertainty on the subject (Self et al., 1997; Emile-Geay et al., 2008).

Baldini et al. (2015) used ice core, volcanological and speleothem data to suggest that unusually large volcanic events (i.e. VEI 5 or greater) might be responsible for abrupt millennial-scale shifts in the global climate characterised by rapid periods of warming in Greenland and apparently synchronous cooling in Antarctica, termed Dansgaard-Oeschger (DO) events. DO events are typically characterised by extremely rapid warming over a period of 20–50 years, followed by a period of relatively warmer climate which may last several centuries to millennia (Mogensen, 2009). The timing of DO events is largely constrained by the examination of oxygen isotopes from Greenland ice cores (Dansgaard et al., 1993), and multiple possible explanations for their occurrence have been suggested, including solar forcing, meltwater injections and oscillations in ocean-atmosphere interactions. Baldini et al. (2015) argue that following an exceptionally large eruption, such as the supereruption of Lake Toba approximately at 75 kya, the ensuing atmospheric temperature asymmetry would have caused sufficient disruption to global circulation patterns to initiate a series of positive feedbacks, including sea ice expansion, increased surface albedo, and weakening of the Atlantic meridional overturning circulation (AMOC). Similar feedback loops with volcanic triggers have been implicated as factors in multiple other Quaternary cooling events (Baldini et al., 2015). Miller et al. (2012) also suggest that the onset of the Little Ice Age (approximately 1300 CE) may have been triggered by the occurrence of four eruptions that were rich in sulfates in quick succession, based on measurements of stratospheric aerosol loadings by Gao et al. (2008).

On a global scale, there is substantial evidence that the emplacement of unusually large igneous provinces (i.e. flood basalt volcanism) may be linked to rapid periods of massive global climate change. Most of these events are estimated to have occurred on a timescale of approximately 1 Myr (Hofmann et al., 1997), and are frequently linked to sudden shifts in the global climate, as well as to mass extinction events (McLean, 1985; Campbell et al., 1992; Courtillot and Renne, 2003; Bond and Wignall, 2014). During the formation of the Deccan Traps, for example, at the Cretaceous/Tertiary boundary at approximately 65 Ma, it is thought that around 5×10^{17} mol of CO_2 may have been released into the atmosphere at a rate of 3.9×10^{11} to 9.6×10^{11} mol CO_2 per year (McLean, 1985). It has been estimated that the same eruption

could also have released 10,000 Tg of SO_2 over a decade (Self et al., 2006). In addition, it is thought that flood basalt events (which may attain aggregate volumes of several thousand cubic kilometres (Coffin and Eldholm, 1994)) may also cause significant contact metamorphism of overlying and underlying sedimentary basin rocks (such as carbonates, coal or organic-rich shale), generating further quantities of greenhouse gases (Ganino and Arndt, 2009), particularly CO_2. Estimating the climatic impact of flood basalt events is greatly complicated by the apparently contradictory effects of the two major gases released. While stratospheric SO_2 generally has a cooling effect, as discussed above, CO_2 is a greenhouse gas, and in sufficient atmospheric concentrations causes significant surface warming. However, whether such concentrations of CO_2 could have been achieved remains disputed; while some models predict a net greenhouse effect (Caldeira and Rampino, 1990; Dessert et al., 2001), others argue that the volumes of CO_2 released would have been small in comparison to the natural atmospheric reservoir, particularly in ambient greenhouse conditions, such as those of the late Cretaceous (Self et al., 2006). Thus, the controlling factor in terms of atmospheric change is likely to be the quantity of SO_2 emissions, making the net effect likely to be one of cooling (Schmidt et al., 2016).

Flood volcanism has also been suggested as a contributing factor in the mid-Jurassic Pliensbachian-Toarcian second order mass extinction event, most notable in the depletion of bivalves and other marine invertebrate species as a result of an oceanic anoxic event (OAE)(Aberhan and Fürsich, 2000). Palfy and Smith (2000) link the event to the synchronous Karoo-Ferrar flood volcanism, which occurred in southern Gondwana (modern southern Africa/Antarctica) 184–179 Ma (Duncan et al., 1997). Based on U−Pb ages for the flows within the Karoo Traps and ocean sediments from the Toarcian OAE, Palfy and Smith (2000) suggest that heightened extinction rates were sustained for approximately 4 Ma, reaching a peak at 183 Ma. This correlates neatly with the peak of flood volcanism, in which approximately 1×10^6 km^3 of material is believed to have been extruded over the course of ~1 Myr (Duncan et al., 1997; Riley et al., 2006). Though the topic is still debated (Svensen et al., 2007; Ikeda and Hori, 2014), the OAE is believed to have been at least partially triggered by volcanic CO_2 release, coupled with multiple unrelated synchronous events, most notably massive methane hydrate dissociation (Hesselbo et al., 2000). The suggested contribution of multiple secondary factors to the extinction event, such as enhanced global mercury deposition (Percival et al., 2015) and a proliferation of endemic species during the late Pliensbachian (Aberhan and Fürsich, 2000), ties into the argument presented by Wignall (2005) - that while volcanic CO_2 emissions may initiate major perturbations to the global carbon cycle, other factors occurring either as a result of or unrelated to the initial eruption are likely to be necessary to cause major climatic change. Whether the emplacement of large igneous provinces may be ultimately responsible for, or merely a contributing factor to any subsequent mass extinction events remains to be determined. Nevertheless, it is clear that wide-scale interplay between the Earth's atmospheric and geospheric systems both exists and has existed in the past on a range of scales, and will continue to do so for the foreseeable future.

3. The potential for a volcanic response to climate change

3.1. Proposed mechanisms

3.1.1. Climate, glacier response and the icelandic low

The majority of studies attempting to model the effect of a warming climate on volcanic eruption frequency are performed in the context of the Icelandic glaciers and volcanoes, though the same link may potentially exist in other sites (see Section 5.2). The relatively rapid response of the Icelandic glaciers to fluctuations in oceanic currents is well documented (Bond et al., 1997; Rahmstorf, 2002; Björnsson and Pálsson, 2008). Numerous sources of proxy data for the reconstruction of palaeoclimate indicate multiple periods of oceanic cooling in the North Atlantic over the past 10 ka BP (Watson et al., 2016b); in particular, decreased sediment productivity across multiple Icelandic lakes suggests a significant cooling event at approximately 6.4 ka BP (Geirsdóttir et al., 2013), and geochemical analysis of a Greenland ice core by Mayewski et al. (1997) shows fluctuations in the concentration of sodium (Na +), which may indicate a deepening of the Icelandic Low atmospheric system between 3.5 and 2.5 ka BP. The strengthening of regional wind speeds which would occur following the onset of a deeper Icelandic Low would result in enhanced transportation of sea salts, resulting in greater concentrations present in the ice core (Mayewski et al., 1997). However, ice core records of the Holocene do indicate that variations in Earth's climate were of a lower amplitude than those seen during the Pleistocene, suggesting that the climate has been more stable in the past 12,000 years than at any point in the last 100,000 (O'Brien et al., 1995; Mayewski et al., 2004).

Evidence of glacial advance in the south, centre and north of Iceland coincides with the climatic cooling events described above (Gudmundsson et al., 1997; Kirkbride and Dugmore, 2001; Kirkbride and Dugmore, 2006). Kirkbride and Dugmore (2006) suggest that, as smaller glaciers are more susceptible to the impacts of climatic forcing, they may account for the vast majority of short-term glacial expansion effects. Larger ice sheets, such as Vatnajökull, have a longer response time -- the total lag time between significant climatic changes and glacial response is typically between 10 and 1000 years (Jóhannesson, 1985).

Possibly the most important factor in understanding the response of the cryosphere to a warming climate, particularly in northern Europe, is alterations to global thermohaline circulation patterns. The North Atlantic Deep Water (NADW) is a key component of this system. Benthic oxygen isotope, cadmium and ^{13}C data from sediment cores imply that a relative shallowing of the current coincides with warming phases, while ebbs may be linked to rapid cooling, such as the Younger Dryas (12.9–11.7 ka BP) (Boyle and Keigwin, 1987). Changes to thermohaline circulation patterns have been identified as *`a major factor in forcing the climate signal and in amplifying it'* (Bond et al., 1997), and it is thought that even small perturbations to the system may have the potential to cause regional temperature changes on the order of several degrees (Rahmstorf, 1996). On a regional scale, many factors related to a warming climate have been identified as major drivers of terrestrial glacier retreat, though the components with the greatest impact are likely to be increased atmospheric temperatures, increased precipitation, and the growth of supraglacial lakes (Reynolds, 2000; Björnsson and Pálsson, 2008).

3.1.2. The unloading effect

The `unloading effect' refers to crustal deformation (specifically uplift) as a response to deglaciation. Isostatic rebound occurs after a load (such as a large glacier) is removed from the lithosphere, and has been directly or indirectly observed in Iceland (Sigmundsson, 1991; Sigvaldason et al., 1992), northern Europe (Lambeck et al., 1998) and North America (James and Morgan, 1990). It is also generally accepted that rapid decreases in pressure (rapid on a geological timescale; that is to say, on the order of at least a few centuries) cause an increase in the extent of decompression melting of the mantle (Asimow et al., 1995). It may therefore be seen how an association between the two factors may be plausible.

The divergent boundary beneath Iceland is already the source of large quantities of decompression melting (Slater et al., 2001). However, Jull and McKenzie (1996) estimate that the removal of 2 km of ice would increase the melt fraction by approximately 0.2%, though the increase in melt generation as a response to unloading is non-linear. Schmidt et al. (2013) go further, suggesting that the Icelandic uplift due to glacial isostatic adjustments (currently estimated at 25–29 mm/yr (Auriac et al., 2013)) has resulted in an annual melt production increase of 100–135% since 1890. Much of this new material is believed to be

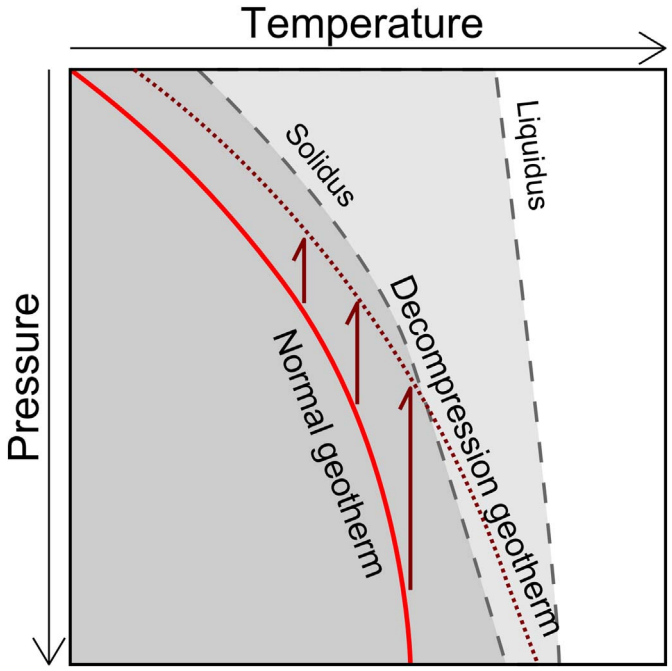

Fig. 2. Example pressure-temperature diagram illustrating how decompression may alter the geotherm of a magma body, allowing for the production of greater quantities of partial melt. Rapid upwelling of the mantle causes a sudden decrease in pressure, altering the geothermal gradient to such a point that it intersects the solidus, allowing melting to begin.

concentrated beneath central Iceland, with approximately 20% located in the mantle beneath Vatnajökull, a region containing some of the island's most productive volcanic centres, such as Grímsvötn (Schmidt et al., 2013). Even on a smaller scale, minor alterations in the crustal stress fields surrounding shallow magma fields may have a dramatic impact on the likelihood of an eruption, particularly at volcanic centres with glacial caps (Albino et al., 2010). Watson et al. (2016a, 2016b) draws a correlation between the depth of the Icelandic Low (as determined through analysis of the GISP2 Na + record (Mayewski et al., 1997)) and the frequency of explosive Icelandic eruptions over the last 7000 years. Their findings indicate that in both instances of Na + increase, volcanic activity on Iceland decreased significantly. There was a lag of approximately 600–700 years between climate alteration and geodetic response, which the authors attribute to the delay in the glacial reaction, and the time taken for new excess magma due to adiabatic melt to reach the surface (Fig. 2).

3.2. Evidence for a volcanic response

3.2.1. Tephrochronology and 'cryptotephra'

Many of the current research efforts investigating a geospheric response to global warming utilise the rapidly developing field of tephrochronology in an attempt to reconstruct the relative frequency of past volcanic events (Dugmore, 1989; Hall and Pilcher, 2002; Davies, 2015). `Cryptotephra' refers to particles of volcanic ash which are not visible to the naked eye, typically being $ < $125 mum (Lane et al., 2014). These particles are often concentrated into layers within well-preserved sediment, such as in lake beds or peat bogs (Hall and Pilcher, 2002), and can provide useful isochrons across multiple sites within an area (Lane et al., 2014; Watson et al., 2016a).

Previously, cryptotephra has been used primarily as a dating and correlation tool in geological and archaeological fields (Lowe, 2011). However, more recent studies have focused on volcanological applications, such as the reconstruction of undocumented eruptions (Sun et al., 2016; Martin-Jones et al., 2016), and – on a wider scale – the analysis of past patterns of volcanic eruptions (Connor et al., 2006), and the transportation of ash particles (Watson et al., 2016b). Watson et al. (2017) use cryptotephra layers acquired from peat and lake sediments to estimate the recurrence interval of Icelandic ashfall across Northern Europe. Using data representing the past 1000 years, the study estimates an average return interval of approximately 44 years (a 20% chance of occurrence within a given 10-year period), based on samples from Germany, Scandinavia, Ireland, Great Britain, Poland and the Faroe islands (Swindles et al., 2011). Swindles et al. (2011) report an apparent increase in the number of ash-fall events affecting Europe over the past 1500 years; however, it is unclear whether this is due to a true increase in volcanic activity during this period, or is an artefact of sampling intensity and improved methodology. It is also possible that more recent events are preferentially preserved in the geological record, and as such assessments of ashfall frequency based solely on tephra will always represent a minimum estimate (Watson et al., 2017).

The assignment of a given tephra or cryptotephra horizon to a particular eruption relies heavily on geochemical analysis of glass shards, in combination with other physical and historical constraints, such as ^{14}C dating, wiggle-match dating techniques and ice core chronologies, where applicable (Swindles et al., 2010; Swindles et al., 2013) (Fig. 3). Various uncertainties still remain in the use of the technique, and the geochemical analysis of individual shards is not yet routine in tephra studies. However, by dating individual tephra layers, it is possible to estimate the relative frequency of volcanic events in a given area. In recent years, collaborative database resources such as Tephrabase (www.tephrabase.org) have emerged in an effort to catalogue the glass shard geochemistry of historic eruptions, greatly smoothing the process of cryptotephra identification.

Analysis of cryptotephra layers can also provide other valuable insights into the processes and characteristics of prior eruptions. For example, the shape and vesicularity of ash shards may provide information about the conditions under which they were formed and transported (Heiken, 1974; Colucci et al., 2013). It is well recognised that the dominant shape of tephra shards (particularly regarding the ratio of the longest to the shortest axis) has a significant effect on the distance those shards may be transported before settling (Wilson and Huang, 1979; Folch, 2012). The concentrations of shards (also known as `tephra loading') may be affected by the distance of the site from the source volcano, or by ambient conditions at the time of emplacement (Langdon and Barber, 2004; Rea et al., 2012).

3.2.2. Modelling efforts

Many studies within the past two decades have attempted to evaluate the effect of ice loading on volcanic activity, both via numerical modelling or through evaluation of historical evidence. Jull and McKenzie (1996) endeavoured to model the effect mathematically, utilising data obtained from tephrochronology of the Dyngjufjöll region of North Iceland. Their results indicated that the removal of 2 km of ice would have an effect approximately equivalent to a 0.6 km upwards shift in the melting column (although it should be noted that the thickest glacier currently in existence –- the Taku glacier in Alaska –- is < 1.5 km thick (Robert and Hermans, 2000)). Jull & McKenzie go on to estimate that total deglaciation of Iceland would increase overall melt production rates by a factor of 30 over a period of 1000 years.

More recent studies have produced more conservative results. Pagli and Sigmundsson (2008) modelled the maintenance of isostatic equilibrium within the lithosphere using the assumption of an elastic plate overlying an isotropic, incompressible, viscoelastic half-space. Adopting contemporary measurements of ice loss and uplift beneath Vatnajökull (Pagli et al., 2007), the study found that, while present rates of ice thinning increase the volume of magma by approximately 0.014 km^3/yr, the effects are confined within existing regions of volcanic activity. Their model also concluded that volcanoes peripheral to the ice cap, such as Kverkfjöll or Bárdarbunga, were more likely to be affected than those close to the centre, such as Grímsvötn; however, while admitting that the effects of increased melt production might be

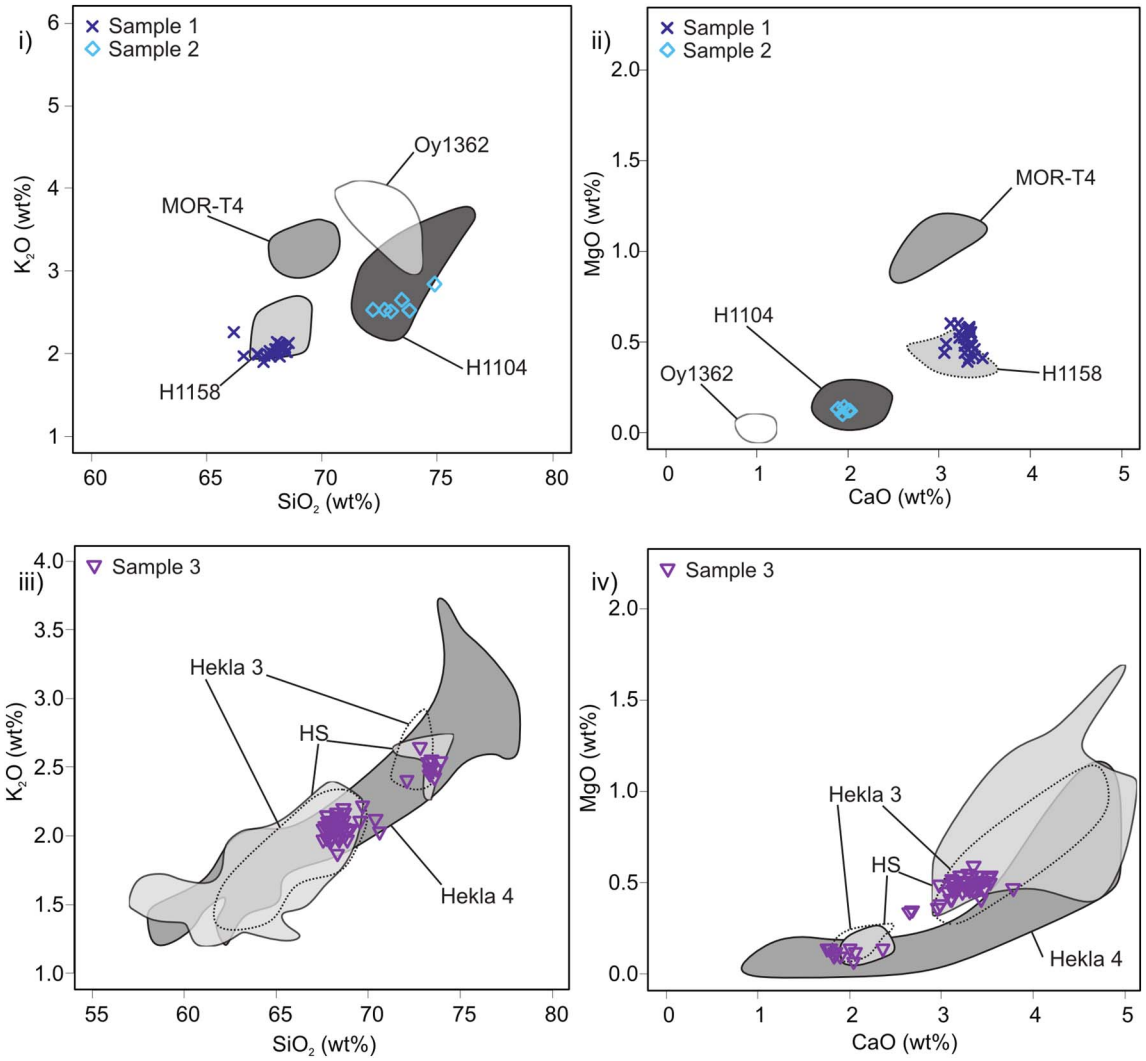

Fig. 3. Bi-plot geochemical analyses of three tephra samples collected from a peat bog in the Shetland Isles (Swindles, unpublished data), compared with the known geochemical signatures of seven historic Icelandic eruptions (grey polygons) (Newton et al., 2007). This example illustrates how cryptotephra which falls into a particular geochemical 'envelope' may be ascribed to a single eruption. In this case, sample one (blue x's; seen in plots (i) and (ii)) most closely matches the H1158 eruption (Hekla), sample 2 (cyan diamonds; plots (i) and (ii)) is most similar to H1104, and sample 3 (purple triangles; plots (iii) and (iv)) is similar to the Selsund (HS) 1800–1750 cal. BC eruption. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

offset by intrusive processes and glacio-isostatic stresses, the study ultimately asserts that the likelihood of a large volcanic eruption within the region is increased by the retreat of the overlying glacier. The results of Jellinek et al. (2004), Albino et al. (2010) and Schmidt et al. (2013) echo this inference.

4. Areas of uncertainty

4.1. Gaps in the tephra record

The analysis of tephra and cryptotephra remains a relatively recent field of study. The current tephra record for Icelandic eruptions contains many spatial gaps, introducing an element of uncertainty into the analyses of fallout areas and eruption frequencies. While it is possible that these gaps represent regions of minimal fallout (i.e. locations which may not commonly experience ashfall due to prevailing meteorological conditions), it is also highly likely that they are purely an artefact of research intensity (Watson et al., 2016a, 2016b). Swindles et al. (2011) present a database of Holocene tephra records across northern Europe, noting that the abundance of data recorded in Ireland and Scandinavia is much greater than in other regions – for example, only one published tephrostratigraphy exists for southern England (Matthews, 2008). Lawson et al. (2012) also provides an analysis of 22 Holocene tephra deposits found in north western Europe, again noting the geographical bias resulting in the underrepresentation of certain continental areas (such as Spain, southern Germany, Belgium and the Netherlands) while also indicating spatial gaps in northern Scandinavia and the western Baltic (Lawson et al., 2012). Additionally, there is a question of glass shard preservation and reworking following deposition - meteorological conditions, vegetation and (more recently) anthropogenic factors may affect the likelihood of fallout preservation (Watson et al., 2016a, 2016b). The tephra chemistry may also play a role in preservation - basaltic glass is more readily dissolved by acidic depositional environments than rhyolitic, resulting in the preferential preservation of silicic eruptions (Lawson et al., 2012). To enable a complete understanding of the processes governing the emplacement of these deposits, it is imperative to establish whether these omissions indicate a true absence of tephra horizons in the locations in question, or if they are simply an artefact of sampling bias.

4.2. Volcanic and tectonic processes

Unfortunately, as our understanding of volcanic processes remains incomplete, so too does our ability to fully predict the response of

volcanic systems to external stimuli. Taking Iceland as an example once again, there remains considerable uncertainty over the variability of rifting across the region (Saemundsson, 1974; Metzger and Jónsson, 2014), and whether large scale changes in the rate and geographical trends of the main axis of rifting might be linked to the presence of a deep mantle plume or `hotspot' (Ofeigsson et al., 2013; Karson, 2016). The present-day rifting zone in eastern Iceland is thought to have become active at around 4–3 Ma (Saemundsson, 1974; Sinton et al., 2005), and to have remained approximately static since that time, with the exception of a brief eastwards shift of the Spar fracture zone roughly 3 Ma (Meyer et al., 1972). It is thought that this section of the rifting zone may have migrated incrementally eastwards in order to accommodate westward drift of the lithospheric plates over a stationary plume. Periods of increase in base rifting activity (such as the major rifting episodes known to have occurred at 12 ka, 11 ka, 10 ka and 3 ka) correspond with periods of enhanced eruption rates, particularly in Iceland's Northern and Western volcanic zones (Magnusdottir et al., 2013). Therefore, any major deviations in underlying tectonic and volcanic processes must be taken into account when attempting to assess the impact of deglaciation. Changes in the rate of rifting are likely to cause centennial variations in eruption frequency (Larsen et al., 1998), while fluctuations in mantle plume activity may cause multi-millennial changes (Óladóttir et al., 2011). However, Watson et al. (2016a, 2016b) argues that such pulses are unlikely to simultaneously affect multiple sites at varying distances from the central spreading ridge in precisely the same manner, hypothetically allowing the signal produced by ice loading to be separated from other factors.

Another issue raised in opposition to the hypothesis that the unloading effect might increase volcanic eruption frequency is that the pressure changes associated with ice retreat may also increase the capacity of the crust to capture melt. Hooper et al. (2011) used a numerical model based around radar and GPS measurements of the Kverkfjöll volcanic system to show how relaxation of the stress fields surrounding the volcano might support intrusion rather than eruption of magma. However, their findings also indicated that dyke orientation is a major factor in determining crustal storage capacity, and that changes in crustal loading alter the conditions required for dyke initiation (Albino et al., 2010). The overall conclusion reached by Hooper et al. was that, while deglaciation might increase magmatic storage capacity in the short term, ultimately increased mantle melting would become the dominant factor.

5. The potential for future work

5.1. A more comprehensive record of past volcanism

While evidence of past volcanic eruptions are typically well-preserved in both the proximal record (i.e. in visible tephra layers and flow deposits), and often also in the distal record as cryptotephra, in many areas the dataset of past events may be considered to be incomplete. Though many sources suggest an apparent increase in the frequency of large volcanic events in Iceland over the past 2 ka (Zielinski et al., 2002; Óladóttir et al., 2011), it is highly possible that inference is largely a result of the preferential preservation of younger ash layers (Watson et al., 2016a, 2016b), an increase in the number of studies, and recent improvements in research techniques, such as advances in geochemical analysis. A thorough campaign of investigation, centred particularly around the examination of the distal record and addressing the identified spatial gaps (as previously discussed), is necessary to confidently evaluate the past levels of volcanic activity, both in Iceland and in other locations. Efforts to this end are currently ongoing in northwestern and continental Europe (Swindles et al., 2011; Lawson et al., 2012; Watson et al., 2016b) and more recently in North America and Greenland (Pyne-O'Donnell et al., 2012; Mackay et al., 2016), but there is also great potential for such work to be conducted in other parts of the world, as evidenced by the discovery of Holocene cryptotephra in Peru (attributed to the Ecuadorian Eastern Cordillera) (Watson et al., 2015). However, the effect of deglaciation on volcanism in the near future is likely to be more substantial in the northern hemisphere, as glacier and ice sheet coverage in that hemisphere is more widespread. Additionally, while the focus has hitherto been on explosive events (as these are more likely to leave distal deposits in the geological record; Swindles et al., 2011), there is significant evidence that the greatest quantities of volcanic sulfate loading may occur as a result of effusive eruptions (Krueger et al., 1996; Schmidt, 2013). Though explosive eruptions are more likely to deliver stratospheric ash and therefore present a greater danger to aviation, from a climatological perspective it may be of interest to compare the levels of climate forcing resulting from different eruption regimes and compositions.

5.2. Quantifying the unloading effect

The issue of geographic sampling bias is also present in models of future changes related to glaciation. Most attempts to model a volcanic response to ice load variations focus on examples from Iceland (Sigmundsson, 1991; Sigvaldason et al., 1992; Pagli and Sigmundsson, 2008; Sigmundsson et al., 2010). A more global view of this effect may offer new insights, and may provide important data to advise policy beyond Europe's airspace. Through combining Smithsonian Global Volcanism Database and the Randolph Glacier Inventory (GLIMS, 2017; see Fig. 4), it is possible to identify several areas worldwide in which:

i. Significant volcanic activity has occurred during the Holocene
ii. A glacier or large ice sheet ($> 1000 km^2$) currently exists

Assuming the current trends of atmospheric warming and glacier retreat continue (Rogelj, 2013), it is reasonable to hypothesise that these highlighted areas may experience a geospheric response to isostatic unloading. While the atmospheric and societal effects of this would in some cases be minimal - increased eruptions in the Antarctic regions, for example, are unlikely to have a significant climatic effect due to their high latitude (Oman et al., 2005), and their remoteness reduces the risk posed to commercial flights - in other areas, such as Canada and Alaska, the impact could be considerably greater.

6. Conclusions

1. As the subject of rapid climate change becomes ever more pertinent to our society, it is increasingly important to understand how such changes may affect the other aspects that govern the workings of our planet. While the atmosphere, geosphere, cryosphere and other facets of the natural world may be considered separately for the purposes of scientific study, in truth none exist in isolation and each represents only part of a complex, interconnected system. The intricate economical and societal structures we have constructed around the aviation industry alone necessitate a more in-depth knowledge of the interplay between volcanic systems and the climate, highlighting the need for further study.
2. Explosive volcanic eruptions may cause significant climatic cooling effects if sufficient quantities of sulphuric aerosol particles achieve stratospheric injection. It is believed that some eruptions, such as the 75 kya Toba event, may have caused a series of positive feedback loops, enhancing the initial cooling effect by several centuries and causing migration of the ITCZ with ensuing changes to circulation and precipitation patterns.
3. Though flood basalt eruptions are frequently linked to long-term climate change and mass extinction events, there is lively debate concerning the cooling influence of aerosol release versus the greenhouse effect of CO_2. While it has been estimated that 5×10^{17} mol of CO_2 may have been emitted during the formation of the Deccan Traps, it has also been argued that this quantity would still have been small in comparison to ambient conditions.

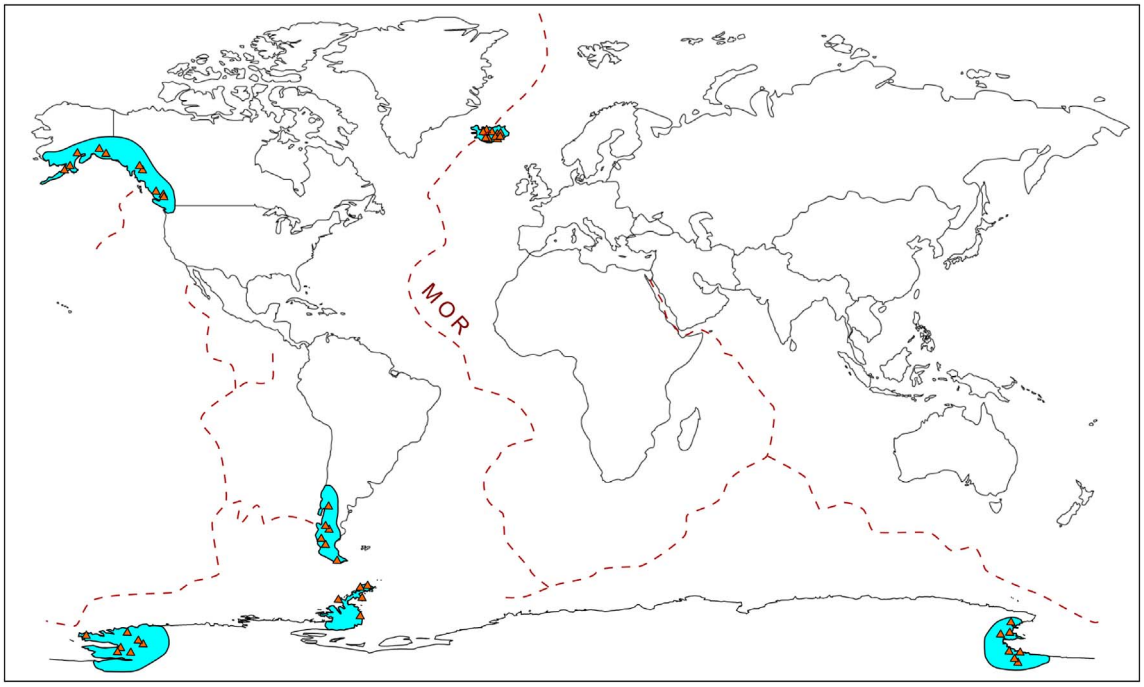

Fig. 4. Multiple areas worldwide meet the following criteria: That they have 1. displayed significant volcanic activity within the past 11,500 years, and 2. currently have one or more large glaciers or ice sheets. These areas are typically within polar/sub-polar latitudes, and are marked in blue. Volcanoes active within the past 5000 years are indicated with red triangles. Mid-oceanic ridges are marked with red dotted lines. The most significant identified regions in which the unloading effect may exert an influence are Alaska/western Canada, southern Chile/Argentina, Iceland, and several regions in coastal Antarctica, including the Antarctic Peninsula and the perimeter of the Ross Ice Shelf (Global Volcanism Program, 2013). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Isostatic rebound in response to glacial unloading is presented as a viable mechanism for a volcanic response to climate change. Adiabatic melting following deglaciation of Iceland is visible both in historical records and in present-day studies of Vatnajökull. It has been estimated that melt production may have increased between 100 and 135% since 1890.
5. Studies of tephra and cryptotephra provide invaluable insights into the frequency of volcanic ash cloud occurrences, and may also provide information on the nature of individual eruptions. Current studies of ash deposition suggest that eruptions which transport significant volumes of ash over continental Europe have a return interval of approximately 56 years, based on depositional records.
6. Numerical models of the `unloading effect' confirm the hypothesis that crustal uplift in response to deglaciation is very likely to cause increased decompression melting. While increased fracturing and intrusion may provide greater storage capacity for upwelling material in the short-term, most models find that the likelihood of a large volcanic eruption is raised by the retreat of an overlying glacier.

Acknowledgements

This review was prepared while Claire Cooper held a Leeds Anniversary Research Scholarship at the University of Leeds.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

References

Aberhan, M., Fürsich, F.T., 2000. Mass origination versus mass extinction: the biological contribution to the Pliensbachian–Toarcian extinction event. J. Geol. Soc. 157 (1), 55–60.

Adams, J.B., Mann, M.E., Ammann, C.M., 2003. Proxy evidence for an el Niño-like response to volcanic forcing. Nature 426 (6964), 274–278.

Air Transport Action Group, 2016. Aviation Benefits beyond Borders Global Summary 2016.

Albino, F., Pinel, V., Sigmundsson, F., 2010. Influence of surface load variations on eruption likelihood: application to two Icelandic subglacial volcanoes, Grímsvötn and Katla. Geophys. J. Int. 181 (3), 1510–1524.

Asimow, P.D., Hirschmann, M.M., Ghiorso, M.S., O'Hara, M.J., Stolper, E.M., 1995. The effect of pressure-induced solid-solid phase transitions on decompression melting of the mantle. Geochim. Cosmochim. Acta 59 (21), 4489–4506.

Auriac, A., Spaans, K.H., Sigmundsson, F., Hooper, A., Schmidt, P., Lund, B., 2013. Iceland rising: solid Earth response to ice retreat inferred from satellite radar interferometry and viscoelastic modelling. J. Geophys. Res. Solid Earth 118 (4), 1331–1344.

Baldini, J.U., Brown, R.J., McElwaine, J.N., 2015. Was millennial scale climate change during the last glacial triggered by explosive volcanism? Sci. Rep. 5.

Björnsson, H., Pálsson, F., 2008. Icelandic glaciers. Jökull 58, 365–386.

Bluth, G.J., Doiron, S.D., Schnetzler, C.C., Krueger, A.J., Walter, L.S., 1992. Global tracking of the SO_2 clouds from the June, 1991 Mount Pinatubo eruptions. Geophys. Res. Lett. 19 (2), 151–154.

Boer, J.G., Flato, G., Reader, M.C., Ramsden, D., 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: experimental design and comparison with the instrumental record for the 20th century. Clim. Dyn. 16, 405–425.

Bond, D.P.G., Wignall, P.B., 2014. Large igneous provinces and mass extinctions: an update. Geol. Soc. Am. Spec. Pap. 505, 29–55.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. Science 278 (5341), 1257–1266.

Boyle, E.A., Keigwin, L., 1987. North Atlantic thermohaline circulation during the past 20, 000 years linked to high-latitude surface temperature. Nature 330 (6143), 35–40.

Caldeira, K., Rampino, M.R., 1990. Carbon dioxide emissions from Deccan volcanism and a K/T boundary greenhouse effect. Geophys. Res. Lett. 17 (9), 1299–1302.

Campbell, I.H., Czamanske, G.K., Fedorenko, V.A., Hill, R.I., Stepanov, V., 1992. Synchronism of the Siberian traps and the Permian-Triassic boundary. Science 258 (5089), 1760–1763.

Coffin, M.F., Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. Rev. Geophys. 32 (1), 1–36.

Colucci, S., Palladino, D.M., Mulukutla, G.K., Proussevitch, A.A., 2013. 3-D reconstruction of ash vesicularity: insights into the origin of ash-rich explosive eruptions. J. Volcanol. Geotherm. Res. 255, 98–107.

Connor, C.B., McBirney, A.R., Furlan, C., 2006. What is the probability of explosive eruption at a long-dormant volcano. Stat. Volcanol. 1, 39–48.

Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. Compt. Rendus Geosci. 335 (1), 113–140.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjörnsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364 (6434), 218–220.

Davies, S.M., 2015. Cryptotephras: the revolution in correlation and precision dating. J. Quat. Sci. 30, 114–130.

Dessert, C., Dupré, B., Francois, L.M., Schott, J., Gaillardet, J., Chakrapani, G., Bajpai, S.,

2001. Erosion of Deccan traps determined by river geochemistry: impact on the global climate and the 87Sr/86 Sr ratio of seawater. Earth Planet. Sci. Lett. 188 (3), 459–474.
Dugmore, A., 1989. Icelandic volcanic ash in Scotland. Scott. Geogr. Mag. 105, 168–172.
Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J., Duncan, A.R., 1997. The Timing and Duration of the Karoo Igneous Event, Southern Gondwana. Oregon State University Faculty Publications, College of Earth, Ocean and Atmospheric Sciences.
Emile-Geay, J., Seager, R., Cane, M.A., Cook, E.R., Haug, G.H., 2008. Volcanoes and ENSO over the past millennium. J. Clim. 21 (13), 3134–3148.
Fischer, E.M., Luterbacher, J., Zorita, E., Tett, S.F.B., Casty, C., Wanner, H., 2007. European climate response to tropical volcanic eruptions over the last half millennium. Geophys. Res. Lett. 34 (5).
Folch, A., 2012. A review of tephra transport and dispersal models: evolution, current status, and future perspectives. J. Volcanol. Geotherm. Res. 235, 96–115.
Franklin, B., 1784. Meteorological imaginations and conjectures. Memoirs and Proceedings of Manchester Literary and Philosophical Society 2 (122).
Ganino, C., Arndt, N.T., 2009. Climate changes caused by degassing of sediments during the emplacement of large igneous provinces. Geology 37 (4), 323–326.
Gao, C., Robock, A., Ammann, C., 2008. Volcanic forcing of climate over the past 1500 years: an improved ice core based index for climate models. J. Geophys. Res.-Atmos. 113 (D23).
Geirsdóttir, Á., Miller, G.H., Larsen, D.J., Ólafsdóttir, S., 2013. Abrupt Holocene climate transitions in the northern North Atlantic region recorded by synchronized lacustrine records in Iceland. Quat. Sci. Rev. 70, 48–62.
Global Land Ice Measurements from Space, 2017. Randolph Glacier Inventory. v. 5.0. (Downloaded 12 Jan 2017).
Global Volcanism Program, 2013. In: Venzke, E. (Ed.), Volcanoes of the World, v. 4.5.3. Smithsonian Institution (Downloaded 12 Jan 2017). https://doi.org/10.5479/si.GVP.VOTW4-2013.
Grindle, T.J., Burcham Jr., F.W., 2003. Engine damage to a NASA DC-8-72 airplane from a high-altitude encounter with a diffuse volcanic ash cloud. In: NASA Technical Reports. 20030068344.
Gudmundsson, M.T., Sigmundsson, F., Björnsson, H., 1997. Ice–volcano interaction of the 1996 Gjálp subglacial eruption, Vatnajökull, Iceland. Nature 389 (6654), 954–957.
Guffanti, M., Mayberry, G.C., Casadevall, T.J., Wunderman, R., 2009. Volcanic hazards to airports. Nat. Hazards 51 (2), 287–302.
Guffanti, M., Casadevall, T.J., Budding, K., 2010. Encounters of aircraft with volcanic ash clouds; a compilation of known incidents, 1953–2009 (no. 545). In: US Geological Survey.
Hall, V.A., Pilcher, J.R., 2002. Late-Quaternary Icelandic tephras in Ireland and Great Britain: detection, characterization and usefulness. The Holocene 12, 223–230.
Haug, G.H., Hughen, K.A., Sigman, D.M., Peterson, L.C., Röhl, U., 2001. Southward migration of the intertropical convergence zone through the Holocene. Science 293 (5533), 1304–1308.
Haywood, J.M., Jones, A., Bellouin, N., Stephenson, D., 2013. Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall. Nat. Clim. Chang. 3 (7), 660–665.
Heiken, G., 1974. An Atlas of Volcanic Ash.
Hesselbo, S.P., Gröcke, D.R., Jenkyns, H.C., Bjerrum, C.J., Farrimond, P., Bell, H.S.M., Green, O.R., 2000. Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event. Nature 406 (6794), 392–395.
Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., Pik, R., 1997. Timing of the Ethiopian flood basalt event and implications for plume birth and global change. Nature 389 (6653), 838–841.
Hooper, A., Ófeigsson, B., Sigmundsson, F., Lund, B., Einarsson, P., Geirsson, H., Sturkell, E., 2011. Increased capture of magma in the crust promoted by ice-cap retreat in Iceland. Nat. Geosci. 4 (11), 783–786.
Horwell, C.J., 2007. Grain-size analysis of volcanic ash for the rapid assessment of respiratory health hazard. J. Environ. Monit. 9 (10), 1107–1115.
Horwell, C.J., Baxter, P.J., 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. Bull. Volcanol. 69, 1–24.
Hwang, Y.T., Frierson, D.M., Kang, S.M., 2013. Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. Geophys. Res. Lett. 40 (11), 2845–2850.
Ikeda, M., Hori, R.S., 2014. Effects of Karoo–Ferrar volcanism and astronomical cycles on the Toarcian oceanic anoxic events (Early Jurassic). Palaeogeogr. Palaeoclimatol. Palaeoecol. 410, 134–142.
Jacoby, G.C., Workman, K.W., D'Arrigo, R.D., 1999. Laki eruption of 1783, tree rings, and disaster for northwest Alaska Inuit. Quat. Sci. Rev. 18, 1365–1371.
James, T.S., Morgan, W.J., 1990. Horizontal motions due to post-glacial rebound. Geophys. Res. Lett. 17 (7), 957–960.
Jellinek, A.M., Manga, M., Saar, M.O., 2004. Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. J. Geophys. Res. Solid Earth 109 (B9).
Jóhannesson, T., 1985. The response time of glaciers in Iceland to changes in climate. Ann. Glaciol. 8, 100–101.
Jull, M., McKenzie, D., 1996. The effect of deglaciation on mantle melting beneath Iceland. J. Geophys. Res. Solid Earth 101 (B10), 21815–21828.
Karson, J.A., 2016. Crustal accretion of thick, mafic crust in Iceland: implications for volcanic rifted margins. Can. J. Earth Sci. 53 (11), 1205–1215 (ja).
Kirchner, I., Stenchikov, G.L., Graf, H.F., Robock, A., Antuña, J.C., 1999. Climate model simulation of winter warming and summer cooling following the 1991 mount Pinatubo volcanic eruption. J. Geophys. Res.-Atmos. 104 (D16), 19039–19055.
Kirkbride, M.P., Dugmore, A.J., 2001. Timing and significance of mid-Holocene glacier advances in northern and central Iceland. J. Quat. Sci. 16 (2), 145–153.
Kirkbride, M.P., Dugmore, A.J., 2006. Responses of mountain ice caps in central Iceland to Holocene climate change. Quat. Sci. Rev. 25 (13), 1692–1707.
Krueger, A.J., Schnetzler, C.C., Walter, L.S., 1996. The December 1981 eruption of Nyamuragira volcano (Zaire), and the origin of the “mystery cloud” of early 1982. J. Geophys. Res.-Atmos. 101 (D10), 15191–15196.
Lamb, H.H., 1970. Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. Philos. Trans. R. Soc. Lond. A 266 (1178), 425–533.
Lambeck, K., Smither, C., Johnston, P., 1998. Sea-level change, glacial rebound and mantle viscosity for northern Europe. Geophys. J. Int. 134 (1), 102–144.
Lane, C.S., Cullen, V.L., White, D., Bramham-Law, C.W.F., Smith, V.C., 2014. Cryptotephra as a dating and correlation tool in archaeology. J. Archaeol. Sci. 42, 42–50.
Langdon, P.G., Barber, K.E., 2004. Snapshots in time: precise correlations of peat-based proxy climate records in Scotland using mid-Holocene tephras. The Holocene 14, 21–33.
Larsen, G., Gudmundsson, M.T., Björnsson, H., 1998. Eight centuries of periodic volcanism at the center of the Iceland hotspot revealed by glacier tephrostratigraphy. Geology 26, 943–946.
Lawson, I.T., Swindles, G.T., Plunkett, G., Greenberg, D., 2012. The spatial distribution of Holocene cryptotephras in north-west Europe since 7 ka: implications for understanding ash fall events from Icelandic eruptions. Quat. Sci. Rev. 41, 57–66.
Lowe, D.J., 2011. Tephrochronology and its application: a review. Quat. Geochronol. 6 (2), 107–153.
Mackay, H., Hughes, P.D., Jensen, B.J., Langdon, P.G., Pyne-O'Donnell, S.D., Plunkett, G., Froese, D.G., Coulter, S., Gardner, J.E., 2016. A mid to late Holocene cryptotephra framework from eastern North America. Quat. Sci. Rev. 132, 101–113.
Magnusdottir, S., Brandsdottir, B., Driscoll, N.W., Detrick, R.S., 2013. Tectonics of the Nafir-Skjálfandadjúp volcanic system, Tjörnes fracture zone, offshore North Iceland: a case of transtensional rifting along a divergent plate boundary. In: AGU Fall Meeting Abstracts. 1. pp. 2382.
Maher, N., McGregor, S., England, M.H., Gupta, A.S., 2015. Effects of volcanism on tropical variability. Geophys. Res. Lett. 42 (14), 6024–6033.
Martin-Jones, C.M., Lane, C.S., Pearce, N.J.G., Smith, V.C., Lamb, H.F., Oppenheimer, C., Asrat, A., Schaebitz, F., 2016. Glass Compositions and Tempo of Post-17 Ka Eruptions from the Afar Triangle Recorded in Sediments from Lakes Ashenge and Hayk. Quaternary Geochronology, Ethiopia.
Matthews, I., 2008. Roman Lode, Exmoor, Devon: Tephrochronology Scientific Dating Report. Research Department Report Series English Heritage.
Mayewski, P.A., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Lyons, W.B., Prentice, M., 1997. Major features and forcing of high-latitude northern hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series. J. Geophys. Res. Oceans 102 (C12), 26345–26366.
Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., 2004. Holocene climate variability. Quat. Res. 62 (3), 243–255.
Mazzocchi, M., Hansstein, F., Ragona, M., 2010. The 2010 volcanic ash cloud and its financial impact on the European airline industry. In: CESifo Forum (Vol. 11, No. 2, 92-100). Ifo Institute for Economic Research at the University of Munich.
McCormick, M.P., Thomason, L.W., Trepte, C.R., 1995. Atmospheric effects of the Mt Pinatubo eruption. Nature 373 (6513), 399–404.
McGuire, B., 2010. Potential for a hazardous geospheric response to future climate changes. Philos. Trans. R. Soc. 368 (1919).
McLean, D.M., 1985. Deccan traps mantle degassing in the terminal cretaceous marine extinctions. Cretac. Res. 6 (3), 235–259.
Meehl, G.A., Washington, W.M., 1996. El Niño-like climate change in a model with increased atmospheric CO_2 concentrations. Nature 382, 56–60.
Metzger, S., Jónsson, S., 2014. Plate boundary deformation in North Iceland during 1992–2009 revealed by InSAR time-series analysis and GPS. Tectonophysics 634, 127–138.
Meyer, O., Voppel, D., Fleischer, U., Closs, H., Gerke, K., 1972. Results of bathymetric, magnetic and gravimetric measurements between Iceland and 70 N. Deutsche Hydrografische Zeitschrift 25 (5), 193–201.
Miller, G.H., Geirsdóttir, Á., Zhong, Y., Larsen, D.J., Otto-Bliesner, B.L., Holland, M.M., Bailey, D.A., Refsnider, K.A., Lehman, S.J., Southon, J.R., Anderson, C., 2012. Abrupt onset of the little ice age triggered by volcanism and sustained by sea-ice/ocean feedbacks. Geophys. Res. Lett. 39 (2).
Mogensen, I.A., 2009. Dansgaard–Oeschger cycles. Encyclopedia of paleoclimatology and ancient. Environment 229–233.
Newhall, C.G., Self, S., 1982. The volcanic explosivity index (VEI) an estimate of explosive magnitude for historical volcanism. J. Geophys. Res. Oceans 87 (C2), 1231–1238.
Newton, A.J., Dugmore, A.J., Gittings, B.M., 2007. Tephrabase: tephrochronology and the development of a centralised European database. J. Quat. Sci. 22, 737–743.
O'brien, S.R., Mayewski, P.A., Meeker, L.D., Meese, D.A., Twickler, M.S., Whitlow, S.I., 1995. Complexity of Holocene climate as reconstructed from a Greenland ice core. Science 270 (5244), 1962–1964.
Oerlemans, J., Anderson, B., Hubbard, A., Huybrechts, P., Johannesson, T., Knap, W.H., Schmeits, M., Stroeven, A.P., Van de Wal, R.S.W., Wallinga, J., Zuo, Z., 1998. Modelling the response of glaciers to climate warming. Clim. Dyn. 14 (4), 267–274.
Ofeigsson, B.G., Hreinsd'ottir, S., Sigmundsson, F., Arnadottir, T., Vogfjord, K., Geirsson, H., Einarsson, P., Jonsson, S., Villemin, T., Fjalar Sigurdsson, S., Roberts, M., April,2013. Geodetic observations in Iceland: divergent plate boundary influenced by a hotspot. In: EGU General Assembly Conference Abstracts (Vol. 15, p. 12560).
Óladóttir, B.A., Larsen, G., Sigmarsson, O., 2011. Holocene volcanic activity at Grímsvötn, Bárdarbunga and Kverkfjöll subglacial centres beneath Vatnajökull, Iceland. Bull. Volcanol. 73 (9), 1187–1208.
Oman, L., Robock, A., Stenchikov, G., Schmidt, G.A., Ruedy, R., 2005. Climatic response to high-latitude volcanic eruptions. J. Geophys. Res.-Atmos. 110 (D13).
Oman, L., Robock, A., Stenchikov, G.L., Thordarson, T., 2006. High-latitude eruptions

cast shadow over the African monsoon and the flow of the Nile. Geophys. Res. Lett. 33, L18711.
Oskarsson, N., Steinthorsson, S., Sigvaldason, G.E., 1985. Iceland geochemical anomaly: origin, volcanotectonics, chemical fractionation and isotope evolution of the crust. J. Geophys. Res. Solid Earth 90 (B12), 10011–10025.
Pagli, C., Sigmundsson, F., 2008. Will present day glacier retreat increase volcanic activity? Stress induced by recent glacier retreat and its effect on magmatism at the Vatnajökull ice cap, Iceland. Geophys. Res. Lett. 35 (9).
Pagli, C., Sigmundsson, F., Lund, B., Sturkell, E., Geirsson, H., Einarsson, P., Árnadóttir, T., Hreinsdóttir, S., 2007. Glacio-isostatic deformation around the Vatnajökull ice cap, Iceland, induced by recent climate warming: GPS observations and finite element modeling. J. Geophys. Res. Solid Earth 112 (B8).
Palfy, J., Smith, P.L., 2000. Synchrony between Early Jurassic Extinction, ocean anoxic event, and the Karoo-Ferrar Flood basalt volcanism. Geology 28 (8), 747–750.
Percival, L.M.E., Witt, M.L.I., Mather, T.A., Hermoso, M., Jenkyns, H.C., Hesselbo, S.P., Al-Suwaidi, A.H., Storm, M.S., Xu, W., Ruhl, M., 2015. Globally enhanced mercury deposition during the end-Pliensbachian extinction and Toarcian OAE: a link to the Karoo–Ferrar large Igneous Province. Earth Planet. Sci. Lett. 428, 267–280.
Pielke, R.A., Avissar, R., Raupach, M., Dolman, A.J., Zeng, X., Denning, A.S., 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. Glob. Chang. Biol. 4 (5), 461–475.
Pilcher, J., et al., 2005. A Holocene tephra record from the Lofoten Islands, Arctic Norway. Boreas 34, 136–156.
Pyne-O'Donnell, S.D., Hughes, P.D., Froese, D.G., Jensen, B.J., Kuehn, S.C., Mallon, G., Amesbury, M.J., Charman, D.J., Daley, T.J., Loader, N.J., Mauquoy, D., 2012. High-precision ultra-distal Holocene tephrochronology in North America. Quat. Sci. Rev. 52, 6–11.
Rahmstorf, S., 1996. Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. Oceanogr. Lit. Rev. 5 (43), 435.
Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. Nature 419 (6903), 207–214.
Rampino, M.R., Self, S., Stothers, R.B., 1988. Volcanic winters. Annu. Rev. Earth Planet. Sci. 16 (1), 73–99.
Rea, H.A., Swindles, G.T., Roe, H.M., 2012. The Hekla 1947 tephra in the north of Ireland: regional distribution, concentration and geochemistry. J. Quat. Sci. 27, 425–431.
Reynolds, J.M., 2000. On the formation of supraglacial lakes on debris-covered glaciers. IAHS Publ. 153–164.
Ridley, H.E., Asmerom, Y., Baldini, J.U., Breitenbach, S.F., Aquino, V.V., Prufer, K.M., Culleton, B.J., Polyak, V., Lechleitner, F.A., Kennett, D.J., Zhang, M., 2015. Aerosol forcing of the position of the intertropical convergence zone since AD 1550. Nat. Geosci. 8 (3), 195–200.
Riley, T.R., Leat, P.T., Curtis, M.L., 2006. Karoo large igneous province: brevity, origin, and relation to mass extinction questioned by new 40Ar/39Ar age data: comment. Geology 34 (1), e109–e110.
Robert, H., Hermans, M., 2000. Alaska's Natural Wonders: A Guide to the Phenomena. 70 Graphic Arts Center Publishing Company.
Robock, A., 2000. Volcanic eruptions and climate. Rev. Geophys. 38 (2), 191–219.
Robock, A., Mao, J., 1992. Winter warming from large volcanic eruptions. Geophys. Res. Lett. 19 (24), 2405–2408.
Robock, Alan, Mass, Clifford, 1982. The Mount St. Helens volcanic eruption of 18 May 1980: large short-term surface temperature effects. Science 216, 628–630.
Robock, A., Matson, M., 1983. Circumglobal transport of the El Chichón volcanic dust cloud. Science 221 (4606), 195–197.
Rogelj, J., 2013. Long-term climate change: projections, commitments and irreversibility. In: IPCC Report, (Chapter 12).
Saemundsson, K., 1974. Evolution of the axial rifting zone in northern Iceland and the Tjörnes fracture zone. Geol. Soc. Am. Bull. 85 (4), 495–504.
Santer, B., Solomon, S., Ridley, D., Fyfe, J., Beltran, F., Bonfils, C., Painter, J., Zelinka, M., 2016. Volcanic effects on climate. Nat. Clim. Chang. 6 (1), 3–4.
Schmidt, A., 2013. Impact of the 1783–1784 AD Laki eruption on global aerosol formation processes and cloud condensation nuclei. In: Modelling Tropospheric Volcanic Aerosol. 65–95 Springer, Berlin Heidelberg.
Schmidt, P., Lund, B., Hieronymus, C., Maclennan, J., Árnadóttir, T., Pagli, C., 2013. Effects of present-day deglaciation in Iceland on mantle melt production rates. J. Geophys. Res. Solid Earth 118 (7), 3366–3379.
Schmidt, A., Skeffington, R.A., Thordarson, T., Self, S., Forster, P.M., Rap, A., Ridgwell, A., Fowler, D., Wilson, M., Mann, G.W., Wignall, P.B., 2016. Selective environmental stress from sulphur emitted by continental flood basalt eruptions. Nat. Geosci. 9 (10), 77.
Self, S., Rampino, M.R., Barbera, J.J., 1981. The possible effects of large 19th and 20th century volcanic eruptions on zonal and hemispheric surface temperatures. J. Volcanol. Geotherm. Res. 11 (1), 41–60.
Self, S., Rampino, M.R., Zhao, J., Katz, M.G., 1997. Volcanic aerosol perturbations and strong El Niño events: no general correlation. Geophys. Res. Lett. 24 (10), 1247–1250.
Self, S., Widdowson, M., Thordarson, T., Jay, A.E., 2006. Volatile fluxes during flood basalt eruptions and potential effects on the global environment: a Deccan perspective. Earth Planet. Sci. Lett. 248 (1), 518–532.
Sigmundsson, F., 1991. Post-glacial rebound and asthenosphere viscosity in Iceland. Geophys. Res. Lett. 18 (6), 1131–1134.
Sigmundsson, F., Pinel, V., Lund, B., Albino, F., Pagli, C., Geirsson, H., Sturkell, E., 2010. Climate effects on volcanism: influence on magmatic systems of loading and unloading from ice mass variations, with examples from Iceland. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 368 (1919), 2519–2534.
Sigvaldason, G.E., Annertz, K., Nilsson, M., 1992. Effect of glacier loading/deloading on volcanism: postglacial volcanic production rate of the Dyngjufjöll area, central Iceland. Bull. Volcanol. 54 (5), 385–392.
Sinton, J., Grönvold, K., Saemundsson, K., 2005. Postglacial eruptive history of the western volcanic zone, Iceland. Geochem. Geophys. Geosyst. 6 (12).
Slater, L., McKenzie, D.A.N., Grönvold, K., Shimizu, N., 2001. Melt generation and movement beneath Theistareykir, NE Iceland. J. Petrol. 42 (2), 321–354.
Solomon, S., 1999. Stratospheric ozone depletion: a review of concepts and history. Rev. Geophys. 37 (3), 275–316.
Stothers, R.B., 1984. The great Tambora eruption in 1815 and its aftermath. Science 224 (4654), 1191–1198.
Stothers, R.B., 1999. Volcanic dry fogs, climate cooling, and plague pandemics in Europe and the Middle East. Clim. Chang. 42 (4), 713–723.
Sun, C., Liu, Q., Wu, J., N'emeth, K., Wang, L., Zhao, Y., Chu, G., Liu, J., 2016. The first tephra evidence for a Late Glacial explosive volcanic eruption in the Arxan-Chaihe volcanic field (ACVF), northeast China. Quat. Geochronol. 40, 109–119.
Svensen, H., Planke, S., Chevallier, L., Malthe-Sørenssen, A., Corfu, F., Jamtveit, B., 2007. Hydrothermal venting of greenhouse gases triggering early Jurassic global warming. Earth Planet. Sci. Lett. 256 (3), 554–566.
Svensson, A., Bigler, M., Blunier, T., Clausen, H.B., Dahl-Jensen, D., Fischer, H., Fujita, S., Goto-Azuma, K., Johnsen, S.J., Kawamura, K., Kipfstuhl, S., 2013. Direct linking of Greenland and Antarctic ice cores at the Toba eruption (74 ka BP). Clim. Past 9, 749–766.
Swindles, G.T., De Vleeschouwer, F., Plunkett, G., 2010. Dating peat profiles using tephra: stratigraphy, geochemistry and chronology. Mires Peat 7.
Swindles, G.T., Lawson, I.T., Savov, I.P., Connor, C.B., Plunkett, G., 2011. A 7000 yr perspective on volcanic ash clouds affecting northern Europe. Geology 39 (9), 887–890.
Swindles, G.T., Lawson, I.T., Matthews, I.P., Blaauw, M., Daley, T.J., Charman, D.J., Roland, T.P., Plunkett, G., Schettler, G., Gearey, B.R., Turner, T.E., 2013. Centennial-scale climate change in Ireland during the Holocene. Earth Sci. Rev. 126, 300–320.
Thordarson, Th., Self, S., 2003. Atmospheric and environmental effects of the 1783–1784 Laki eruption: a review and reassessment. J. Geophys. Res. 108 (D1), 4011.
Watson, E.J., Swindles, G.T., Savov, I.P., Bacon, K.L., 2015. First discovery of Holocene cryptotephra in Amazonia. Sci. Rep. 5.
Watson, E.J., Swindles, G.T., Lawson, I.T., Savov, I.P., 2016a. Do peatlands or lakes provide the most comprehensive distal tephra records? Quat. Sci. Rev. 139, 110–128.
Watson, E.J., Swindles, G.T., Stevenson, J.A., Savov, I., Lawson, I.T., 2016b. The transport of Icelandic volcanic ash: insights from northern European cryptotephra records. J. Geophys. Res. Solid Earth 121 (10), 7177–7192.
Watson, E.J., Swindles, G.T., Savov, I.P., Lawson, I.T., Connor, C.B., Wilson, J.A., 2017. Estimating the frequency of volcanic ash clouds over northern Europe. Earth Planet. Sci. Lett. 460, 41–49.
Webster, P.J., 1994. The role of hydrological processes in ocean-atmosphere interactions. Rev. Geophys. 32 (4), 427–476.
Wignall, P.B., 2005. The link between large igneous province eruptions and mass extinctions. Elements 1, 293–297.
Wilson, L., Huang, T.C., 1979. The influence of shape on the atmospheric settling velocity of volcanic ash particles. Earth Planet. Sci. Lett. 44 (2), 311–324.
Zielinski, G.A., Mayewski, P.A., Meeker, L.D., Whitlow, S., Twickler, M.S., Morrison, M., Meese, D.A., Gow, A.J., Alley, R.B., 2002. Record of volcanism since 7000 BC from the GISP2 Greenland ice core and implications for the volcano-climate system. Climate Change 264, 271.